EXTREME VACUUM TECHNOLOGY INCLUDING CRYOSORPTION, DIFFUSION PUMP AND PRESSURE CALIBRATION STUDIES

by

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PREFACE

The development of several phases of research relating to vacuum science and technology are included in this program. Mr. George Wise of the NASA Lewis Research Center is the technical monitor. This Quarterly Status Report covers the period from 1 May 1965 to 1 August 1965.

The research program is conducted in the Physics Department of the Midwest Research Institute under the direction of Dr. Sheldon L. Levy and Mr. Gordon E. Gross. Research activities were conducted by Dr. Paul Bryant, Mr. Charles Gosselin and Dr. William W. Longley.

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SUMMARY

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A description of cold cathode magnetrons and Penning cells operating as gauges has been developed in terms of the conditions for establishing a discharge and the effects of space charge buildup. Pressure response curves for three commercial gauges (Redhead, Kreisman and G. E. trigger types) were determined by a conductance-regulated, pressure-ratio method using Bayard-Alpert type gauges for reference.

Four characteristics are predicted from the discharge mechanism and correlated with test data for the normal magnetrons: (1) an out-of-strike state characterized by a steady pressure-independent background reading of about 5×10^{-14} Torr; (2) a minimum pressure threshhold for operation (2.7×10^{-12} Torr for Redhead, 1.7×10^{-10} Torr for Kreisman); (3) a range of nonlinear pressure-dependent response above threshhold in which the sensitivity rise with pressure is moderated by space charge buildup; followed by (4) a range of near linear response (slope of 1.04 for Redhead, 1.11 for Kreisman types on a log pressure-log current plot) corresponding to the region of nearly saturated space charge. Differences in response values are correlated with differences in electrode elements, spacings, and voltages for the two magnetron gauge tube designs.

Three response characteristics were determined for the G. E. trigger gauge: (1) a field emission background current which dominates the response below a real pressure of 10^{-10} Torr; (2) a three order of magnitude rise of the pressure dependent discharge between 10^{-10} and 10^{-9} Torr; and a response curve above 10^{-9} Torr which varies around an average slope of 1.25. The operation of a Penning cell such as used in the trigger gauge is similar to that of a magnetron since the electron cloud forms a virtual cathode concentric with the anode. This report therefore concentrates upon the description of magnetron type discharges.

Author

I. INTRODUCTION

A Penning type discharge cell[1] generally consists of a cylindrical or rectangular anode cage with two end plate cathodes which are not concentric with the anode. The G.E. trigger discharge gauge[2] employs a 1/2-in. Penning type cell with some modifications such as a cylindrical rather than a C-shaped magnet and small holes in the end plates for the passage of electrons from a filament mounted just outside of the cell.

A magnetron may be defined as an assembly of two concentric cylindrical electrodes operated in an axial magnetic field. When used as a pressure gauge, the electric and magnetic fields are chosen such that the bulk of the cavity is beyond magnetron cutoff. That is, electrons are not able to travel from cathode to anode unless they lose energy by colliding with gas molecules (see Fig. 1). The gauge, therefore, remains in an out-of-strike state, unless the gas pressure is high enough to support a discharge. The present report investigates this phenomenon as well as the basic operation of magnetron gauges. There are two commercially available gauges which may be described as magnetrons: the NRC Redhead gauge and the GCA Kreisman gauge.

In 1952, Beck and Brisbane[3] reported a series of experiments using both normal and inverted magnetron arrangements. A central wire and a cylinder with several bulkhead discs were employed as electrodes. The sensitivity was higher when used as an inverted magnetron. The device had two disadvantages: a background current due to field emission, which was equivalent to about 10^{-8} Torr; and a power law rather than a linear relation between cathode current and gas pressure. However, a useful gauge circuit was designed using proper resistance values and a nonlinear meter scale.

Haefer[4] developed a magnetron for an investigation of striking characteristics of a gaseous discharge in transverse electric and magnetic fields. The magnetron was found to strike at pressures below the sustaining discharge level for Penning cells designed up to that time. Much of the existing theory of magnetron gauge operation has been adapted from Haefer's work, which was based on the assumption of a negligible space charge and a uniform electric field. The first assumption holds only prior to striking, and the second does not hold for the electrode arrangements used in pressure gauges.

The next advance in magnetron pressure gauges was made by Hobson and Redhead.[5,6] They eliminated the recording of erroneous field-emission current from the cathode by inserting auxiliary cathodes into an inverted magnetron structure. These additional electrodes shield the main cathode from the anode. Field emission from the auxiliary cathodes is independent of the ion current

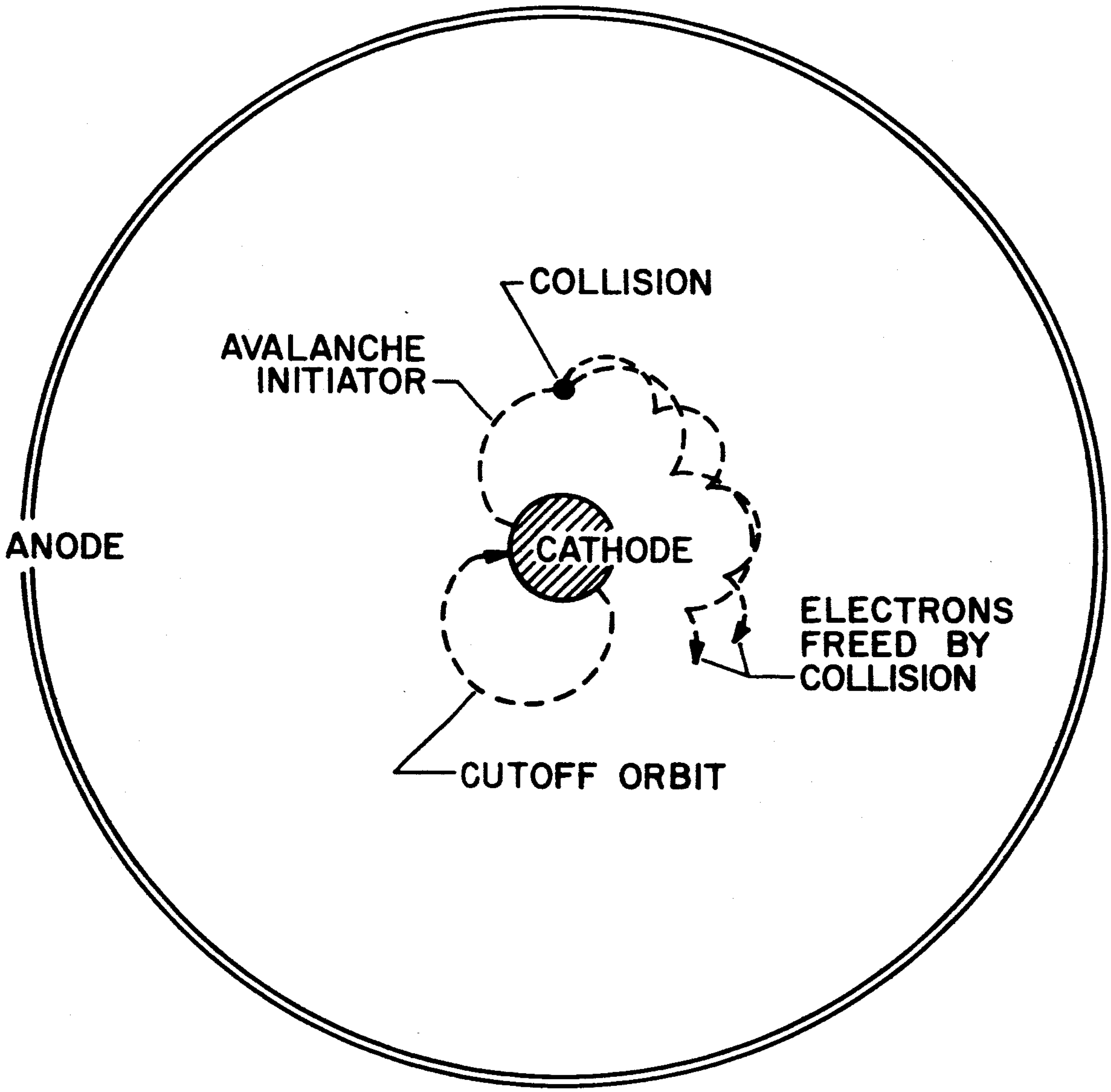

Fig. 1 - Electron Orbits in a Co-Axial Magnetron Structure. Field emitted electrons either return to the cathode or collide with gas molecules to release secondary electrons.

measuring circuitry of the main cathode, thus avoiding an erroneous background current. However, the linear response, which Beck and Brisbane[3] predicted would be obtained near 2,500 gauss, was not attained.

Redhead[7] designed a modification of the normal magnetron structure which had increased field emission over the Beck and Brisbane cathode wire configuration. This design (Fig. 2) placed the plates in contact with the central cathode bar and inserted large rings as auxiliary cathodes. Thus, field emission was again removed from the ion current measuring circuit. A response near linearity (slope 1.035 on a log current -- log pressure plot) from about 5×10^{-10} Torr to 10^{-3} Torr, and a departure from linearity (slope 1.66) below 5×10^{-10} Torr was discovered. At extremely low pressures, additional photoelectric action was necessary to insure starting. Using this modified design, Hobson[8] reported a limiting pressure measurement of 1.5×10^{-12} Torr in a liquid helium cooled system. The limit was assumed to be due to helium permeation of the walls of the glass system.

Kreisman has devised several versions of cold cathode normal magnetrons placed in metal envelopes to avoid a breakage problem. One of these models, which has no indication of auxiliary cathodes (see Fig. 2), is available commercially. Also, the Redhead gauge design was modified for flight tests[9] by removing the auxiliary cathodes; a significant alteration of response occurred as described later.

The expected characteristics of a magnetron with the space charge necessary to operate as an ionization gauge are discussed below. A pressure-ratio technique used to test commercial gauges is also described. The quantitative results of these tests are found to be consistent with the qualitative features of the expected operation of pressure dependent discharges which are limited by space-charge. The results are correlated with the design features of the G. E. triggered gauge, the regular Redhead gauge, with auxiliary cathodes, as well as the Redhead flightgauge and Kreisman design, without auxiliary cathodes.

II. THEORY

Previous studies[5-7] on the theory of magnetron gauge operation have neglected the space charge alteration of the electric field which occurs during operation. These discussions of the Townsend α coefficient also neglect the variation of the mean electric field over the cycloidal orbits described between collisions. A fully self-consistent technique for estimating the behavior of the magnetron gauge would necessarily include the space charge alteration of the electric field, the variation of electric field overthe "hypercycloidal" (in normal magnetrons) or "hypocycloidal" (in inverted magnetrons) orbits described between collisions, and the pressure dependence of the space charge density at any radial position.

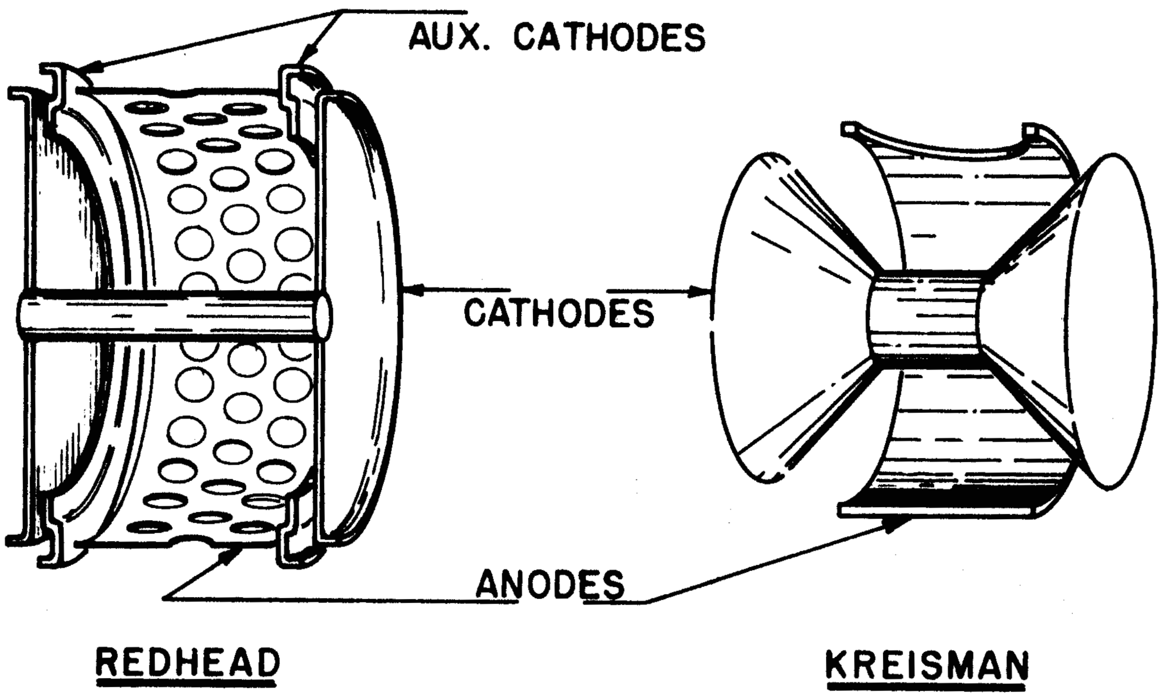

Fig. 2 - Electrode Configurations of Commercial Magnetron Gauges, Shown in Cut-Away

Haefer's[4] qualitative discussion of space charge effects indicated that the potential could be adjusted so that the number of ionizing collisions made by an electron traveling from the cathode to the anode would be essentially the same under space charge limited operation as under space charge free conditions. He demonstrated that the necessary change in voltage was essentially proportional to the current-to-pressure ratio, as long as the model used was applicable. However, there was no argument presented that the current is proportional to the first power of the pressure under normal operating conditions.

From the electron and ion lifetime studies of Haefer[4] and Redhead,[6] one would expect to find a negative space charge in a magnetron operated at pressures below 10^{-3} Torr. Jepsen[10] has discussed the effect of a uniform space charge density on the electric field for a magnetron structure. As he indicates in the preliminary discussion, the uniform space charge density is only a convenient fiction with which to work.

The consideration of space charge buildup as pressure increases can be accomplished only qualitatively until the electron loss mechanisms and the variation of space charge with position and pressure are better known. The basic electron loss mechanism has been assumed to be their arrival at the anode after several collisions. However, there is the possibility of axial motion of the electrons taking them to points where the end effects on the electric field and the constancy of magnetic field direction will permit them to leave the active volume of the gauge by collision-independent paths. In the extremely high vacuum range, orbital lifetimes of electrons traveling from cathode to anode may extend to hours,[4,6] if electronic oscillations do not interfere. When the cycloidal behavior of the electrons is considered, these long lifetimes and the velocity differences of the electrons can easily lead to slipstream instabilities which could return some electrons to the cathode and send others to the anode without the electron-molecule interactions postulated in the Townsend discharge theory.

The qualitative picture of space charge moderated operation of a magnetron gauge will now be given. At extremely low pressure, the loss mechanisms will preclude the maintenance of a discharge. However, a background reading is present which is not affected by removal of the magnet, a fact which confirms the lack of ion current in this cutoff state.

Field emitted electrons will describe short cutoff orbits starting and ending on the cathode. (As Redhead[7] indicates, these paths actually can cover a significant part of the cathode-anode distance.) Field emission between auxiliary cathode and anode is an important source of electrons when there are few electron-molecule collisions within the main volume of the discharge.

In addition, the electric fields around the cathode endplates may permit an electron freed from one endplate to migrate to the opposite endplate in a spiral path. However, the electron density in the gauge volume will be negligible until the number of electrons colliding with gas molecules is significant.

When the pressure is increased to a lower operating threshold, there are enough gas phase collisions to release electrons to cathode-independent paths at a rate which exceeds the loss rate. A space charge then begins to build (see Fig. 1). This cathode-independent space charge is able to produce ions which are then detected at the cathode. The electrometer will change rather suddenly from a steady background value to a threshold ion current plus background reading when the discharge strikes.

As the space charge increases, the secondary electrons caused by ion bombardment of the cathode cylinder will see a lower electric field; and, although the number will probably increase with increasing ion current, the maximum kinetic energy in a complete cycloidal arc and the arc length would be reduced. Field emission from the cathode will also be suppressed. The increase of space charge may eventually lead to a complete inactivation of the central portion of the cathode as an electron source. Thus, the cathode endplates or cones (see Fig. 2) become increasingly important in defining the gamma coefficient for the discharge as pressure increases.

In summary, we would expect magnetron gauge operation to be characterized by (1) absence of a discharge with only a constant background current for very low pressure; (2) a threshold ion current at a pressure dependent on gauge geometry and voltage; and (3) a sharp rise in ion current as pressure increases slightly until space charge saturation is approached.

III. EQUIPMENT

The characteristic response of ion current to pressure for cold cathode gauges was determinded by a conductance-regulated, pressure-ratio method.[11] This technique provided continuous operation of a reference Bayard-Alpert type hot-filament, ionization gauge (BAG) at a pressure two orders of magnitude above the pressure at the test magnetron gauge position (see Fig. 3). Thus, the linear response of a BAG with constant emission current was used to obtain a continuous plot of the response curve for the magnetron gauges without the necessity of lowering the BAG to the level of residual collector current. The constancy of the pressure ratio was confirmed by using two BAG tubes on either side of the known conductance. Of course, the downstream BAG was then required to operate to a pressure below the x-ray photo current value. When corrections for total residual current were made, changes of the downstream gauge were found to remain linear with changes of the upstream gauge within gauge reading error.

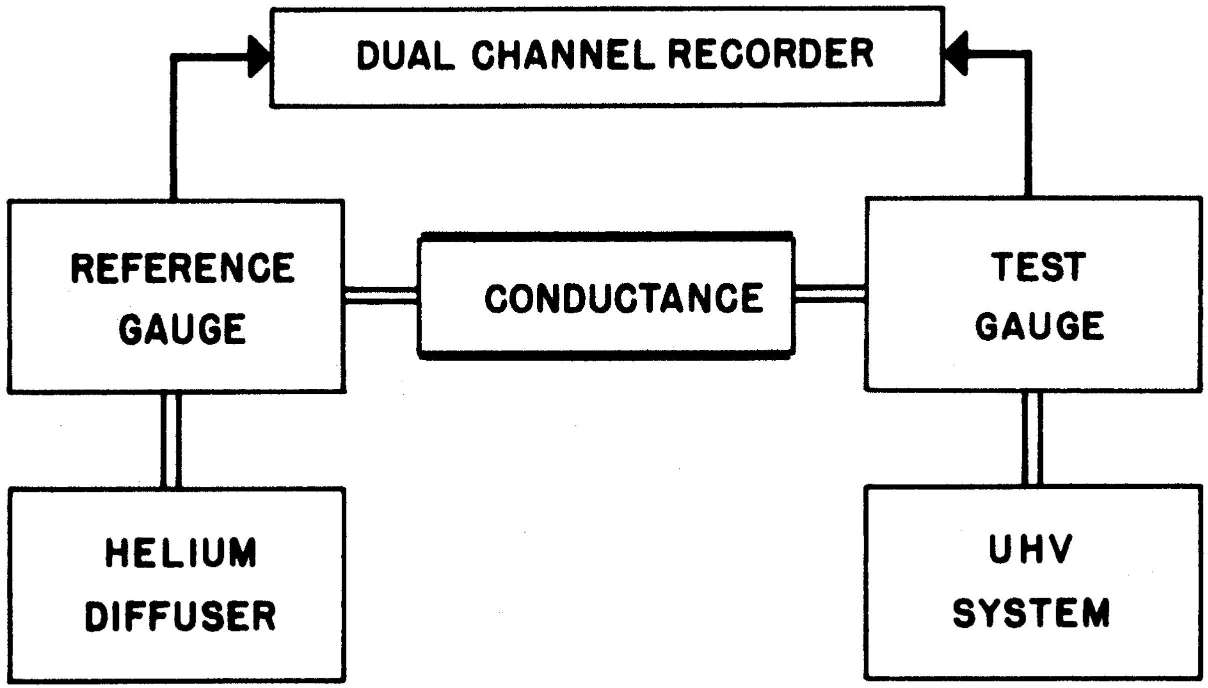

Fig. 3 - Vacuum Gauge Comparison System Employing the Pressure-Ratio Technique. The flow of helium through a fixed conductance establishes a pressure ratio. The ultimate vacuum attainable by the UHV system exceeded the operating range of each magnetron gauge.

The characteristic current-to-pressure response for G. E. trigger, NRC Redhead, and GCA Kreisman gauges were determined to their lowest operating values. The pressure-ratio method was employed for each gauge type. In addition, the Kreisman gauges were studied by direct comparisons to BAG, since the commercial BAG type employed (Varian model UHV-12) covers the full operating range of the commercial Kreisman gauge. The response curve for Kreisman gauges determined by direct comparison, with corrections for residual current in the BAG readings, agreed with the response curve obtained by the pressure ratio method. No correction for residual current in the BAG was required for the set of pressure ratio data, since the two order-of-magnitude ratio permitted operation to the low pressure limit of the Kreisman gauge without operating the BAG below 10^{-8} Torr.

Output currents from the BAG, used as reference gauge, and the cold cathode gauges were simultaneously plotted on a uniform time base, as indicated in Fig. 3 by a two-channel, strip-chart recorder using the recorder output terminals from the commercial control units. Ion currents and background currents were measured with a Cary model 35 vibrating reed electrometer. High voltages were set at the specified values of 4,800 volts for the Redhead type, 4,000 volts for the Kreisman type and 2,000 volts for the G. E. trigger type and regularly monitored with a sensitive Electrostatic Voltmeter. Magnetic field strengths of the permanent magnets were also checked periodically with a gauss meter and found to remain near the specified values. The BAG tubes (Varian model UHV-12) were operated with a grid potential of 130 volts, and an emission current of 4 ma, so that the sensitivity was 25/Torr. Therefore, all operating parameters were carefully maintained at the values specified by the manufacturers of each type gauge tube.

IV. RESPONSE CURVES

The characteristic response curves, determined from a large amount of data using the methods described above, are plotted in Figs. 4, 5, 6 and 7. Actual pressure values in dry air equivalent are plotted on the abscissae, and indicated pressures from the gauge control units are plotted on the ordinates. Ordinate values may be converted to ion current values by multiplication with the dry air sensitivity factors (4.5 amp/Torr for the Redhead, 2.0 amp/Torr for the Kreisman and 2.5 amps/Torr for the G.E. trigger), since the control unit circuits are designed on the assumption of linear response, i.e., constant sensitivity.

The ultra-high vacuum portion of the response curve for Redhead gauges (Fig. 5) shows the following characteristics: (1) a background corresponding to an indicated pressure reading of 5×10^{-14} Torr when the real pressure is below the threshold for operation; (2) a total current value of

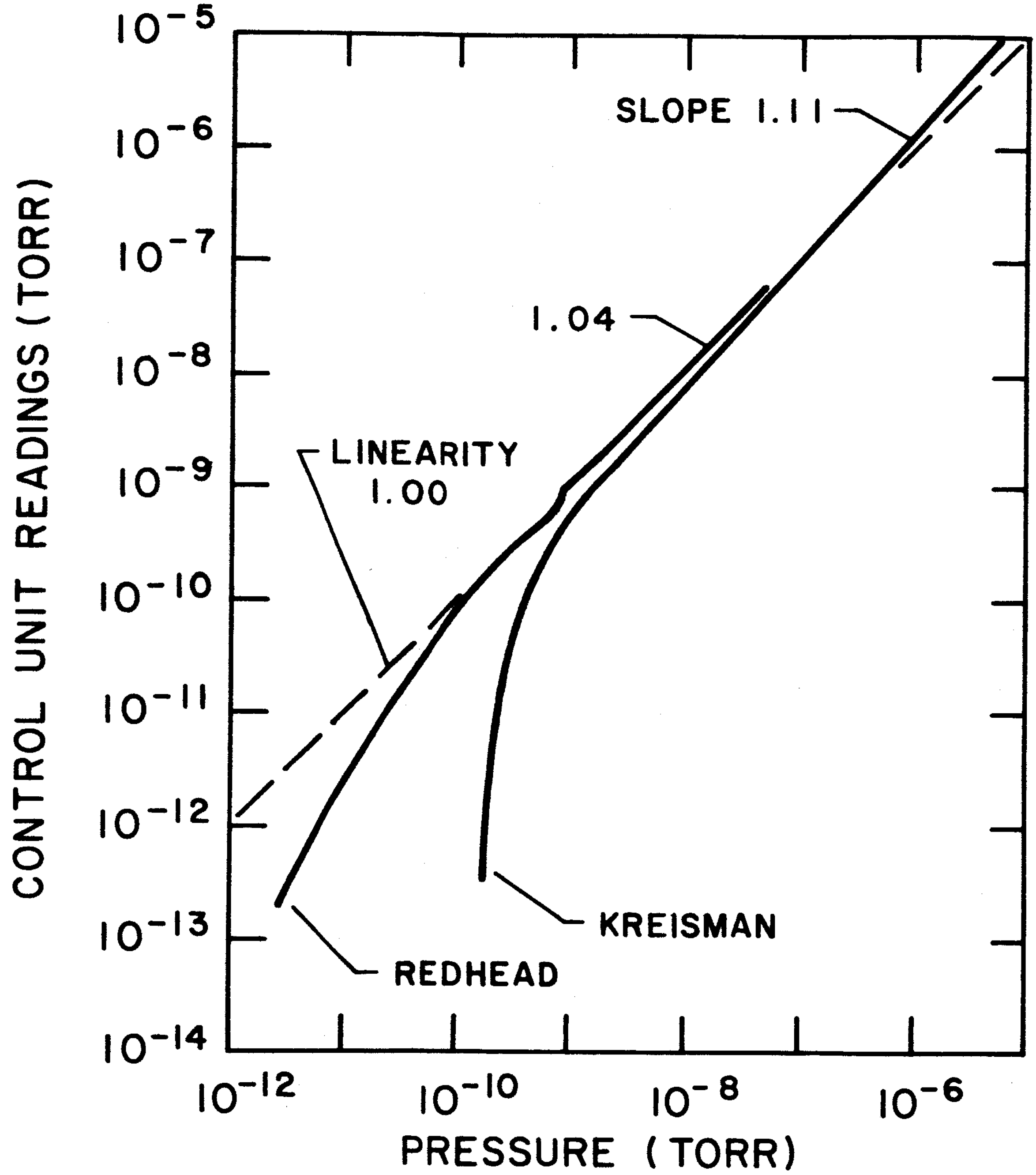

Fig. 4 - Characteristic Response Curves for Two Magnetron Gauge Models (Upper Portion of Redhead Curve Omitted), Showing Differences Which Result from Variations in the Designs

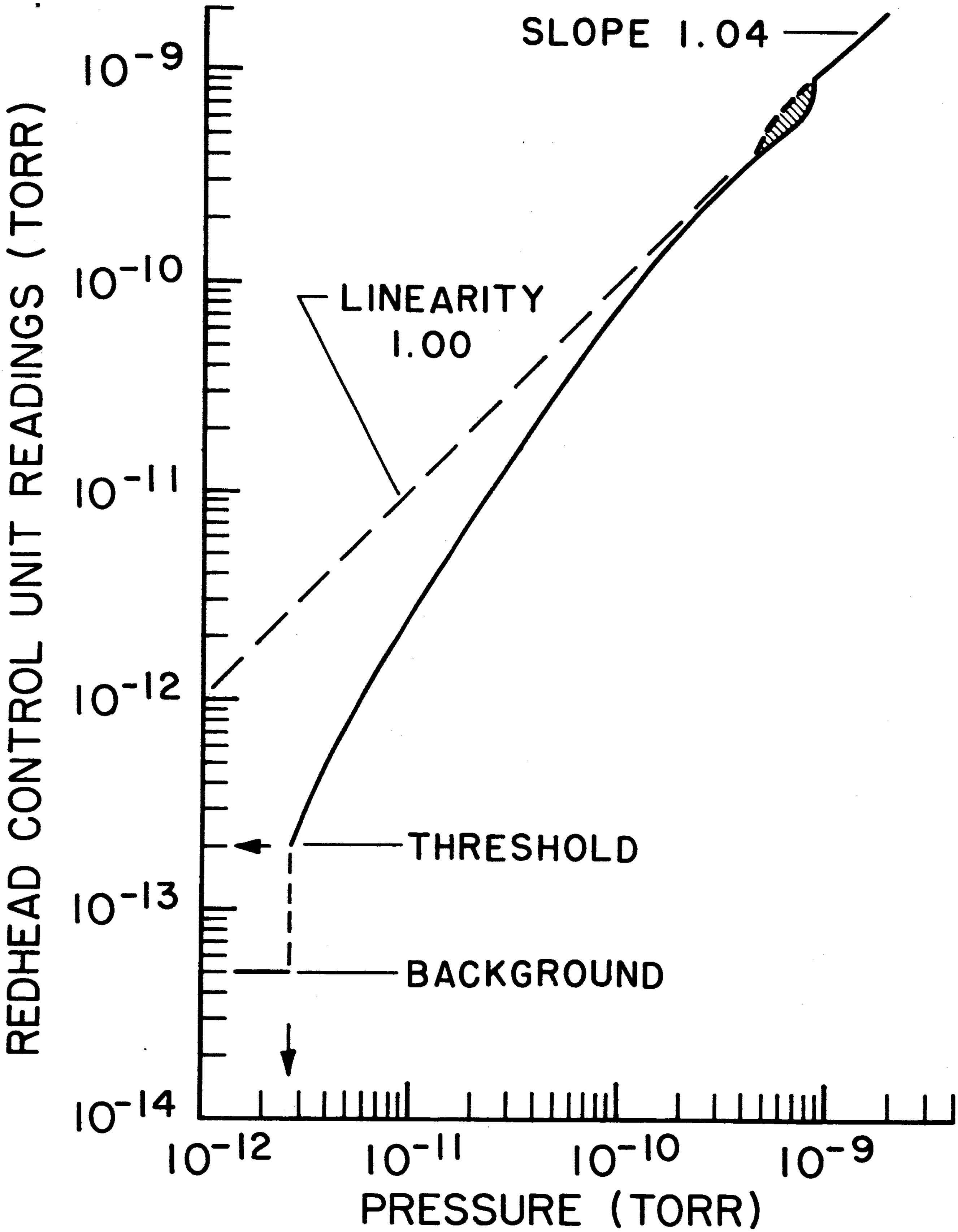

Fig. 5 - Characteristic Response of Clean Redhead Gauges Showing: Background, Operating Threshold, and an Unstable Region

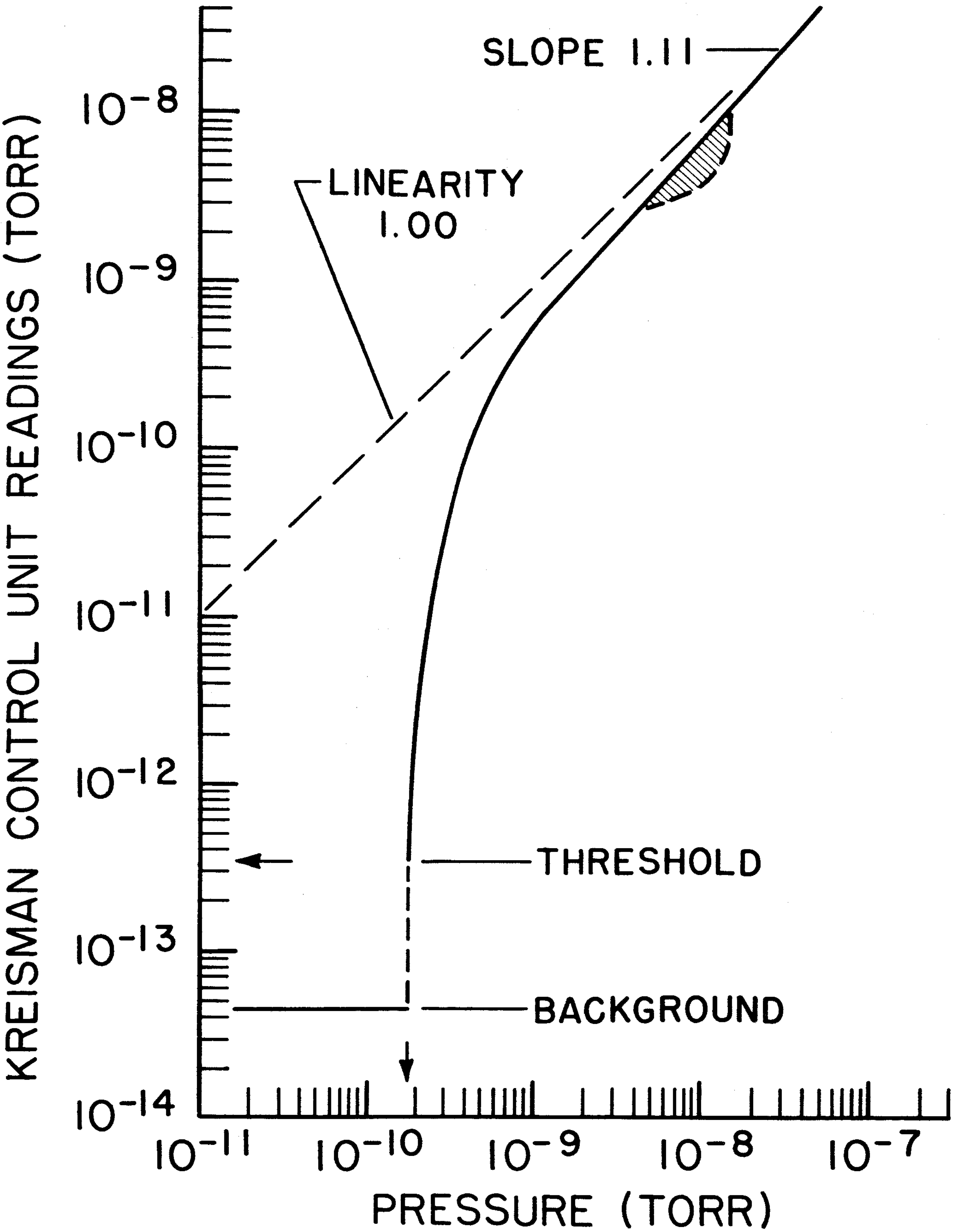

Fig. 6 - Characteristic Response of Clean Kreisman Gauges Showing: Background, Operating Threshold, a Possible Unstable Region and a Sensitivity Rise with Pressure

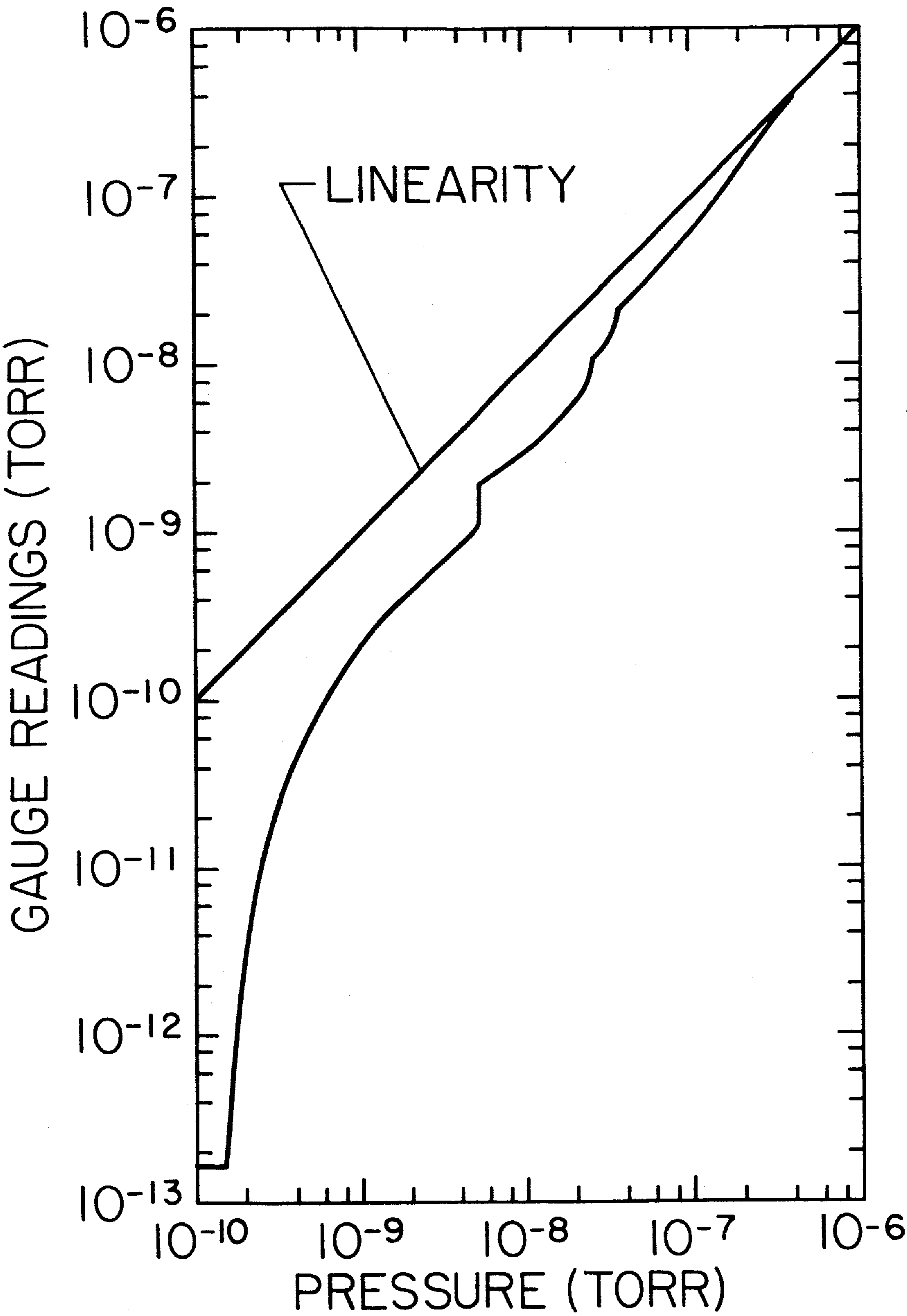

Fig. 7 - Response Curve for a G.E. Trigger Discharge Gauge Operated at 2 Kv. Using a Gauge Factor of 2.5 Amps/Torr, Average Slope is 1.25 above 10^{-9} Torr.

9 x 10^{-13} amp for initiation of a sustaining discharge; this threshold level corresponds to an indicated pressure of 2 x 10^{-13} Torr and a real pressure of about 2.7 x 10^{-12} Torr; (3) a nonlinear response curve for values above threshold with a continuously changing slope approaching linearity near 10^{-9} Torr, due to the continuous buildup of space charge toward a saturated value, i.e., the sensitivity of the gauge increases as space charge increases, until a nearly saturated state is reached at 10^{-9} Torr; (4) a region of instability or resonance around 7 x 10^{-10} Torr characterized by high frequency oscillations in the output current; and (5) a response curve above 10^{-9} Torr which has a nearly linear slope of 1.04 with a slow rise in sensitivity, due to additional buildup of the essetially saturated space charge. The data presented in Fig. 5 represent the best response of clean Redhead gauges operated with the recommended potential of 4,800 volts and a magnetic field of 1,040 gauss.

The ultra-high vacuum portion of the response curve for clean Kreisman gauges (Fig. 6) shows the following characteristics: (1) a background corresponding to an indicated pressure reading of 4.5 x 10^{-14} Torr for any real gas pressure value below 1.7 x 10^{-10} Torr; i.e., for pressures below operating threshold, the gauge remains in the out-of-strike state; (2) a total current value of 7 x 10^{-13} amp for initiation of a discharge; this threshold level corresponds to an indicated pressure reading of 3.5 x 10^{-13} Torr and a real pressure of 1.7 x 10^{-10} Torr; (3) a nonlinear response curve for values above threshold with a continuously moderated slope, due to the self-moderation of space charge buildup; (4) a region of instability around 10^{-8} Torr; and (5) a sensitivity above 10^{-8} Torr which continues to increase with pressure along a response curve of slope 1.11; thus, linear response is not achieved. The latter feature is also found[7] for a Redhead flight gauge from which auxiliary cathodes have been removed.

The threshold phenomenon may be repeatedly observed by raising and lowering the real pressure around the value necessary to sustain a discharge, i.e., 2.7 x 10^{-12} Torr for Redhead and 1.7 x 10^{-10} Torr for Kreisman tubes. To accomplish small pressure changes around the threshold values, the helium diffuser (see Fig. 3) operation is slightly increased and decreased. Although the small pressure changes are recorded by the reference ion gauge, large stepwise changes from the background to the threshold value are indicated by the magnetron gauges. In addition, the magnetron gauges do not respond to pressure changes below the threshold value; i.e., the steady background current or out-of-strike value pertains for all pressures below the threshold level.

V. DISCUSSION AND CONCLUSIONS

The threshold phenomenon may be described in terms of the minimum number of avalanche initiating electrons required for a sustaining discharge. Figure 1 illustrates the process by which field emitted electrons may escape from the cathode and enter the trapping region to promote a sustaining discharge. An avalanche initiating electron may make an ionizing collision with a gas molecule and lose sufficient energy, so that it will travel in a hypercycloidal path which does not intersect the cathode, as in the example shown. The secondary electron produced by ionization normally enters the trapping region of the discharge, also. However, for magnetron devices operated below cutoff, as is the case for both Redhead and Kreisman types, a field emitted electron will execute a cycloidal path which intersects the cathode on the first orbit (see Fig. 1), unless a collision occurs. For the electric and magnetic field values employed in the Redhead and Kreisman gauges, an avalanche will not exist unless a sufficient number of gas molecules exists inside the anode cage to provide the threshold number of avalanche initiating collisions.

The total cathode current corresponding to threshold for the Redhead gauge is 9×10^{-13} amp, including currents from avalanche initiating electrons, ions and background. Since this total value is four times greater than the background, there is a clearly distinguishable difference between operation of the gauge above and below threshold. Even the cleanest tubes exhibit this threshold phenomenon.

Threshold and background values also exist for the Kreisman gauge. However, the real pressure corresponding to threshold is 66 times higher, which suggests that fewer electrons are available for avalanche initiation. Differences between at least two parameters of the gauges may be invoked to predict a difference in avalanche initiating electrons: (1) the recommended operating potential is 800 volts lower for the Kreisman gauge; and (2) the central cathode radius is about double that used in the Redhead gauge (see Fig. 2). These two differences both add to a prediction of lower electric field at the cathode surface, and thus fewer field emitted electrons to start an avalanche in the Kreisman tube.

The continuously-modified, nonlinear-response curve above threshold, and the approach to linear response due to space charge saturation are two additional qualitative characteristics observed experimentally for both magnetron gauges. However, we again note that quantitative values are different for the two designs. The nonlinear response above threshold is steeper for the Kreisman tube, beginning with a slope of 14 and reaching 1.11, whereas the Redhead response curve begins with 2.2 and reaches a nearly linear slope of 1.04.

These differences may be viewed in terms of a rise in sensitivity with pressure. The Kreisman gauge sensitivity increases from 4.0×10^{-3} amp/Torr at threshold to 2.0 amp/Torr at 10^{-7} Torr, while the Redhead gauge sensitivity goes from 3.3×10^{-1} amp/Torr at threshold to 5.0 amp/Torr at 10^{-7} Torr. Thus, the Redhead gauge sensitivity changes by 15 times, while the Kreisman gauge sensitivity changes by 500 times from threshold to a nearly saturated discharge. The greater change in sensitivity for the Kreisman gauge geometry suggests a greater change of the ionization probability in the discharge, due either to an increased amount of space charge or an effective spread of the discharge into a greater volume. The differences in electrode geometry may again be invoked to understand this phenomenon (see Fig. 2). The unique feature of auxiliary cathodes in the Redhead gauge permits a much closer spacing between cathode and anode electrodes; thus, the space charge is better enclosed electrostatically and may be contained within a fixed volume at a saturated value.

It is interesting to note, in closing, that calibration of the flight model Redhead design, from which the auxiliary cathodes were removed, gave a response curve with a slope of 1.15.[7] That is, the flight model responded similarly to the 1.11 slope of the Kreisman design, indicating poorer containment of the discharge. Thus, the data for flight gauges[7] and Kreisman gauges without auxiliary cathodes correlate, while the data from regular Redhead gauges with auxiliary cathodes, and the electrostatically tight anode cage which results, are seen to agree with the space charge buildup and saturation hypothesis described in this report.

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